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<p>The acquired DURIP(96) equipment was used to complement the Focused Research Initiative research project of BMDO/AFOSR on "Photonic Imaging Networks." The DURIP(96) equipment was used to carry out the research in three projects:</p> <ol style="list-style-type: none"> 1. Nonlinear Space-Time Optical Signal Processing with Femtosecond Pulses 2. Robust Quantum and Classical Cryptograph for Security and Privacy in Photonic Imaging Network 3. Artificial dielectrics and diffractive optics with multifunctionality and their applications. 		
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November 10, 1998

Dr. Alan Craig
AFOSR/NE
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

Dear Alan:

Please find enclosed the final technical report for the following grant: F-49620-96-1-0415
entitled Defense University Research Instrumentation Program: "Photonic Imaging Networks."
Should you have any questions about this report, please do not hesitate to contact me.

Sincerely,

A handwritten signature in cursive script that appears to read "Shaya".

Y. Fainman
Professor

19981127 068

Final Technical Report

for

Defense University Research Instrumentation Program(96):
Photonic Imaging Network

Sponsored by

Ballistic Missile Defense Organization

and

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The Regents Of the University of California, San Diego

University of California , San Diego

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Acquired Equipment

1. Tsunami 3941-SIS mode locked titanium-sapphire source of femtosecond pulses with 50 fsec pulsewidth option from Spectra Physics (~ \$50 K)
2. Spitfire-LCX-XK regenerative amplifier from Spectra Physics (~ \$65 K)
3. Merlin-LCX Q-switched YLF regen pump from Spectra Physics (~ \$55 K)
4. OPA 800-1 Optical Parametric Amplifier with $\chi^{(2)}$ option for 2-nd and 4-th harmonic generation and the wavelength extension from Spectra Physics (~ \$50 K)
5. Optical table top and support system from Newport Inc. was required to be able installing the lasers (item#1-4) and set up research experiments (~ \$20 K)

The total cost of the acquired DURIP(96) equipment was \$240 K consisting of \$210 K provided by the BMDO/AFOSR DURIP(96) and the \$30 K matched by UCSD.

Projects Summary using Acquired Equipment

The acquired DURIP(96) equipment was used to complement the Focused Research Initiative research project of BMDO/AFOSR on "Photonic Imaging Networks." The DURIP(96) equipment was used to carry out the research in three projects as summarized below.

Nonlinear Space-Time Optical Signal Processing with Femtosecond Pulses (Y. Fainman, Y. T. Mazurenko, P. C. Sun, K. Oba, D. Marom and D. Panasenko)

The bandwidth and the efficiency of optical communication systems exceed these of electrical cable systems. Electronic devices and systems connected to optical networks may reach bit-rates on the order of 1-10 Gb/s. In contrast, the maximum bit-rate of a photonic network may exceed 1 Tb/s. The 2-3 order-of-magnitude mismatch between fiber and electronic device capacity can be used to increase the speed, reduce latency, increase security and reliability in the transmission and distribution of image information. To implement these applications, we used the acquired DURIP(96) equipment to construct an all-optical pre-processor at the transmitter and a post-processor at the receiver which performs multiplexing and demultiplexing, respectively [1-9]. The multiplexer performing image space-to-time transformation combines relatively slow but parallel in space electronic channels into an ultrahigh bandwidth serial optical channel (i.e., parallel-to-serial conversion), whereas the demultiplexer performs the inverse time-to-image space transformation for processing and/or electronic detection (i.e., serial-to-parallel conversion). For efficient bandwidth utilization, these processors need to be operated at rates determined by the bandwidth of the optical pulses [10]. Such space-time optical processors have been analysed [11] and constructed using the equipment from this DURIP(96) grant and applied for pulse shaping, filtering, and space-to-time multiplexing and time-to-space demultiplexing [1, 2, 12-17]. We also interfaces a space-to-time multiplexing system to an optical fiber and performed transmission of a sequence of 170 fsec pulses. These pulses from the output of the fiber were then introduced into our time-to-space demultiplexing systems [18]. We also developed a new time-domain time-to-space demultiplexer [19] providing a compact and power conversion efficient design. Furthermore, we have started investigation of additional application areas such as efficient signaling using our approach of pulse position modulation for ultrahigh speed data communication [8, 9, 20], potential role of our demultiplexer for high speed A/D conversion [21], and combining our approach with CDMA technique to allow multiple users in a network environment [8, 9, 17].

Another example of using the acquired DURIP(96) equipment exploits applications that will benefit from an optical memory that will store and retrieve information in a format that is suitable for direct interface and transmission through an optical network, thereby, providing optimal performance in terms of hardware complexity, memory and network capacity, bandwidth, and latency. In this example we convert spatial image information into time domain. The corresponding data sequence in time is stored employing spectral domain 3-D volume holographic recording [22-24]. When the stored data is read out of the spectral domain storage system, the output spectrum is converted back into time sequence and sent through the all-optical fiber network to the user node. At the user node the time sequence is converted to lower rate parallel channels in space domain for optical or electronic filtering and detection [16]. Alternatively, we also explored the direct time-domain storage, which shows significantly improved SNR performance due to the fact that the rectangular boundaries of the crystal can be replaced by a smooth synthesized shape that can be established by recording mutual coherence functions of femtosecond pulses [24, 25].

In summary we introduced, analyzed and, using the acquired DURIP(96) equipment, evaluated experimentally a femtosecond pulse storage and imaging techniques useful for demultiplexing and parallel processing sequences of femtosecond pulses. We developed two pulse imaging method, based on 3-wave mixing in nonlinear crystals, one technique based on nonlinear mixing of spectral decomposition waves and the other based on nonlinear interaction directly in the time domain. The spectral domain mixing technique allows converting complex amplitude of an ultrashort temporal pulse signal to a corresponding spatial image that resembles the temporal signal in space. Unlike the commonly used autocorrelator, our method carries both amplitude and phase information of the pulses. We also demonstrate nonvolatile storage of femtosecond pulses in photorefractive LiNbO_3 by recording and readout of spectral holograms at a wavelength of 460 nm and 920 nm, respectively. No degradation was observed after 24 hours readout. The demonstrated spectral domain nonvolatile holographic storage and the femtosecond pulse imaging are useful for broadband information systems applications. We transmitted a sequence of femtosecond pulses through a fiber and detected the output pulses using out pulse imager system. We also developed a time-domain pulse imager, explored the efficient signaling using the pulse position modulation and by combining it with a CDMA methods we are exploring its operation in a network environment. Most recently we have performed nonlinear spectral domain filtering and also conducted preliminary experiments on space-to-time conversion at femtosecond rate based on 4 wave mixing between the temporal and spatial information carrying channels.

Robust Quantum and Classical Cryptography for Security and Privacy in Photonic Imaging Network. (Y. Fainman, R. Rao, L. Milstein, Y. T. Mazurenko, D. Marom, P. C. Sun, B. Slutsky, D. Panasenko)

Our research focussed on experimental realization [26-31] and information theoretic analysis of quantum cryptosystems [27-40]. On the theoretical side, we have studied the relationship between the secrecy capacity of a quantum cryptographic system and such factors as the error rate, line attenuation, and detector quality [32-34]. Quantum eavesdropping strategies and possible defenses against them were also investigated [35-38]. We have introduced and, using the acquired DURIP(96) equipment, conducted preliminary experiments on transmission of photon phase information employing frequency division technique suitable for practical realizations over free space or optical fiber network [26-31]. The advantage of our technique is related to the fact that the phase difference between two signals spectrally separated by a small amount (in our experiments, 80 MHz) is not perceptibly affected by the physical stress to which the fiber carrying them may be subjected. Measurements were performed both with classical strength signals and with photomultipliers used as single photon detectors. Appropriate interfaces between the photomultipliers and the microcomputer controller was also established using the

DURIP(96) grant. In a separate experiment, we also tested and verified that two signals with frequency separation of 80 MHz do not experience noticeable phase delay difference due to dispersion in a fiber under external temperature stress. We are currently investigating design and implementation of frequency-division long distance interferometer using all fiber components. We also continue our research on utilizing optical sources that obey sub-Poisson statistics using second order nonlinear optical crystals.

Our second approach uses classical encryption methods for privacy of next generation ultrahigh bandwidth photonic imaging networks. This work explores secure systems that make use of the large optical bandwidth of ultrashort pulses. The technique combines with optical code-division multiple access using stationary or dynamically varying time delays. We have demonstrated few components that are integral part of this system demonstration, including femtosecond laser pulse spectrum modulation using phase-only computer-generated-holograms [13, 15, 17], or a phase-only spatial light modulators. Each encrypted spectrum will be separated into two parts, and transmitted with an appropriately chosen delay between them. Coherent detection uses a complementary spectral-combining device combined with a sequence of temporal delays which allow the selection of the desired transmitter. The designated receiver will be able to compensate for the time-delay of the corresponding transmitter, combine the two complimentary signals, and use the secure phase-decoder to decrypt the message. The coherent detection using three-wave mixing has been also demonstrated using the acquired DURIP(96) equipment [16-20, 22-24]. The classical encryption system for photonic imaging network privacy employing spread spectrum techniques is currently being further investigated. Our preliminary experiments are found in good agreement with the theoretical analysis.

Artificial dielectrics and diffractive optics with multifunctionality and their applications

(Y. Fainman, F. Xu, P. C. Sun, J. Thomas, R. Tyan, P. Shames, W. Nakagawa, P. Lin)

We have been investigating the diffractive optics with multifunctionality in polarization [41-47] and color [48-50] as well as programmable diffractive optics [51-65] during the last five years employing natural birefringent and electrooptic nonlinear materials. Recently we initiated research into artificial dielectric materials (nanostructures) for photonic device applications. The acquired DURIP(96) equipment also contributed to our characterization effort in the area of artificial dielectrics and diffractive optics. Modern microfabrication techniques (dry etching, electron beam lithography, patterned regrowth, epitaxial growth, laser assisted growth, laser ablation, etc.) allow to artificially fabricate sub-micron micro-structures which modify the dielectric and semiconductor properties such as birefringence, optical nonlinearity or opto-electronic interactions. For example, form birefringence or artificial birefringence effect occurs due to periodic microstructure boundary between two isotropic dielectric materials with different dielectric constants. The form birefringent microstructures posses several unique properties that make them superior compared to these of naturally birefringent materials: (i) high strength of form birefringence, $\Delta n/n$, can be obtained by selecting substrate dielectric materials with large refractive index difference (here Δn and n are the difference and the average effective indices of refraction for the two orthogonal polarizations, respectively), (ii) the magnitude of form birefringence, Δn , can be adjusted by varying the duty ratio as well as the shape of the microstructures, (iii) form birefringence can be constructed using an isotropic as well as anisotropic substrate, allowing to fine tune the anisotropic properties of naturally birefringent materials, and (iv) form birefringent microstructures can be used to modify the reflection properties of the dielectric boundaries. The artificial dielectric anisotropy due to form birefringence [66, 67] has been used to construct polarization optics components as well as polarization selective computer generated holograms [70, 71]. The form birefringence and the

form birefringent computer generated holograms were characterized experimentally using the acquired DURIP(96) equipment.

We further extend this approach by designing a new device that uses unique properties of anisotropic spectral reflectivity (ASR) characteristics of a high spatial frequency multilayer binary grating [70, 71]. The ASR mechanism is based on combining the effects of the form birefringence of a high spatial frequency grating (i.e., grating period is much less than the wavelength of the incident field) with the resonant reflectivity of a multilayer structure. With our approach, the angular field and wavelength range have been largely increased compared to conventional polarization selective beam splitter (PBS) devices. The ASR PBS combine such unique features as compactness, compatibility with semiconductor materials, negligible insertion losses, polarization selectivity for light at normal incidence, high polarization extinction ratios, and operation with waves of large angular bandwidth and from broad spectral range. Some interesting characteristics of the element with ASR characteristics cannot be found in a conventional PBS component. For instance, when our ASR device is designed to operate with normally incident light, it acts as a highly efficient polarization selective dielectric mirror [72-77]. The ASR devices have been fabricated and characterized using the acquired DURIP(96) equipment. Furthermore, our ASR device fabrication method is compatible with conventional microfabrication and can become easily integrable with other photonic devices such as VCSELs, MQW modulators, and photodetectors. Initial experiments with fabricated devices demonstrate good performance. We also extended the ASR design into the third dimension and have shown that using this approach we can design manufacturable photonic crystals [75-77]. The band structures of such photonic crystals have been calculated using our newly developed rigorous electro-magnetic wave modeling tools.

The polarization selective computer generated holograms have been constructed and used for packaging optical interconnects in an optoelectronic VLSI chip [78]. We also developed switching fabric using a transparent optical multistage interconnect network (TOMIN), based on birefringent computer generated holograms technology being developed at UCSD which forms an 8×8 nonblocking interconnection network [79]. The present embodiment of the TOMIN is based on free-space optics. Image transmission between large numbers of I/O ports, requiring switching of ultra-high bandwidths, can be performed using optical multistage interconnection networks (MIN). Polarization based switching has been proposed for 'free-space' MIN for switching and multiprocessor interconnections. We have designed, fabricated and tested a 'folded' optical MIN system that permits switching high-speed signals between multiple input and output nodes using a simple and compact arrangement of diffractive optical and polarization rotation elements. In this system, optical routing is performed using bypass-exchange switches built of polarization sensitive birefringent computer generated holograms (BCGH) combined with electrically addressed polarization rotation devices. This transparent and scalable system can switch multiple high bandwidth communication lines or permit memory access and multiprocessor interconnections.

The reconfiguration of the network is currently limited by the speed of the FLC device. However, we are developing a PLZT based [59-65] polarization rotator array having much faster response times. Advances in fiber amplifiers and polarization compensation in a single mode fiber may enable utilization of polarization dependent all-optical switches using optical fiber input and outputs.

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